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NUMERICAL APPROXIMATIONS OF SELECTED METEOROLOGICAL PARAMETERS RELATED TO CLOUD PHYSICS

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Army Electronics Command
White Sands Missile Range, New Mexico

March 1973

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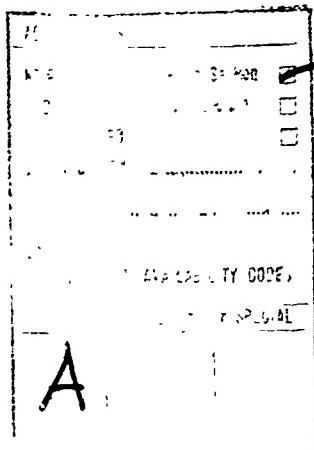
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13. ABSTRACT

Methods of computation and error estimates are presented for numerical approximation of selected meteorological parameters used in the solution of cloud physics problems. These parameters are latent heat, saturation vapor pressure, dew point and wet bulb temperatures, specific heat of liquid water, temperature of the lifting condensation level, change in mass of freely falling water drops, and saturation-adiabatic temperatures. The FORTRAN programming language listings of the approximations are provided in the Appendix.

I

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3. Meteorological Parameters						

II

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NUMERICAL APPROXIMATIONS OF SELECTED

METEOROLOGICAL PARAMETERS

RELATED TO CLOUD PHYSICS

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LIST OF SYMBOLS

Symbol	Subscript	Item	Units Used
c		Specific Heat	$ITcal\ g^{-1}K^{-1}$
	p	air at constant pressure	
	w	liquid water	
e		Water Drop Diameter	m
3		Partial Pressure of Water Vapor	mb
	a	actual	
	s	saturation	
	s_i	saturation over solid water	
	s_w	saturation over liquid water	
	w	saturation at the wet bulb temperature	
log		Common Logarithm (base 10)	
L		Latent Heat of water	$ITcal\ g^{-1}$
	f	fusion	
	s	sublimation	
	v	vaporization	
M		Mass of Water Drop	g
P		Pressure	mb
	a	atmosphere (with no water)	
	t	atmosphere total	
R		Dry Air Gas Constant	$ITcal\ g^{-1}K^{-1}$
rh		Relative Humidity	Percent
t		Time	Sec
T		Temperature	K
	a	dry bulb	
	d	dew point	
	LCL	lifting condensation level	
	m	psuedo-adiabatic	
	s	saturation-adiabatic	
	w	wet bulb	
	x	approximation of saturation-adiabatic	
X		Mixing Ratio	$g\ g^{-1}$
	s	water vapor at saturation	
	w	liquid water	
	z	initial value of X_s	
ε		Ratio of molecular weights of water vapor and dry air	--

INTRODUCTION

The application of techniques for numerical simulation to
various meteorological processes requires that many meteorological
parameter descriptions be subject to individual approximation.
Thus, the accuracy and adequacy of the descriptions are
dependent on the requirements of the individual "simulator."
In many cases the importance of the meteorological parameter
description is subordinate to some broader scale problem; as
such, if the description is deemed adequate, it is normally
used without explanation or comment. As a consequence
there are many methods available for the description of
meteorological parameters, but there is a paucity of information
on how well they describe the parameters. If the accuracy
must be known, then the investigator must either construct
his own approximation or ascertain the accuracy of some
available approximation, either of which can detract from
the solution of a larger problem.

This report contains descriptions of numerical approximating
techniques for meteorological parameters required by the author
and his associates in conjunction with numerical modeling efforts
concerning clouds and fogs [1], [2], [3], [4]. This presentation
is made so that there might be a ready reference to a set
of approximating methods and the accuracies associated with
the calculated parameter values.

The numerical approximations are divided into two groups:
(1) descriptions of meteorological parameters, per se; and (2)
descriptions of meteorological parameters associated with a
meteorological process. The first group covers the latent
heats of water, the saturation vapor pressures of water, the
dew point and wet bulb temperatures, and the specific heat of
liquid water. The second group covers the temperature of the
lifting condensation level, the change of mass of freely
falling water drops, and the temperatures resulting from
saturated adiabatic processes. The method of approximation
and the source of comparative values, as well as the error
as determined relative to the comparative values, is provided for
each parameter. The units for the comparisons are those of the
comparative base, where applicable. In those cases where comparative
values are not available, the basis of the accuracy given is discussed.
When percentage errors are given the value presented is calculated
from

$$\text{Percentage Error} = 100 \; \frac{\text{Calculated value} - \text{Reference value}}{\text{Reference value}} \quad (1)$$

The FORTRAN programming language listing of the approximations is provided in the Appendix in either FUNCTION STATEMENT or SUBROUTINE form as appropriate.

METEOROLOGICAL PARAMETERS

The meteorological parameters described in this section are associated with the state of the atmosphere and are, therefore, essentially definitions of the value of the parameter for the specified state. The parameters covered are those associated with the following: the heat requirements for the change of phase of water; the partial pressure of water vapor over liquid and solid plane water surfaces; the temperature at saturation of air cooled at constant pressure with no change in water vapor content; the temperature of air cooled to saturation at constant pressure; and the specific heat of liquid water.

Latent Heats

The latent heats are associated with the vapor-liquid, vapor-solid, and liquid-solid phase changes of water. The latent heats can be expressed as functions of temperature, T, with the techniques given here using degrees Kelvin (conversion to other temperature units is provided in Table I) and the latent heat expressed in ITcal g^{-1} (conversion to other units is provided in Table II).

The latent heat associated with the liquid-vapor/vapor-liquid phase changes is the latent heat of vaporization, L_v. It can be approximated from

$$L_v = 754.817 - 0.575 \, T \quad (2)$$

The latent heat associated with the solid-vapor/vapor-solid phase changes is the latent heat of sublimation, L_s. It can be approximated from

TABLE I[1]

TEMPERATURE UNIT CONVERSIONS

Unit	Symbol	Unit	Symbol	Conversion
Kelvin	K	Centigrade	C	K - 273.16
		Fahrenheit	F	1.8 (K - 273.16) + 32
		Rankine		1.8 (K - 273.16) + 491.69

TABLE II[2]

ITcal g^{-1} UNIT CONVERSIONS

1.0 International Steam Tables Calorie (ITcal) = 1.00032 cal_{15}

$$1.0 \text{ ITcal } g^{-1} = 4.18684 \times 10^7 \text{ cm}^2 \text{ sec}^{-2}$$
$$4.18684 \times 10^3 \text{ m}^2 \text{ sec}^{-2}$$
$$4.5057 \times 10^4 \text{ ft}^2 \text{ sec}^{-2}$$

[1]The conversions given here are based on the values provided by List [5, p. 17].

[2]The conversions given here are based on the values provided by List [5, p. 14].

$$L_s = 98.777 + \left[335566.953 - |T-238|^2\right]^{\frac{1}{2}} \quad (3)$$

The latent heat associated with the solid-liquid/liquid-solid phase changes is the <u>latent heat of fusion</u>, L_f. It can be approximated from

$$L_f = (1.7757 - 0.0023245T)T - 0.012 |T-243| - 231.494 \quad (4)$$

The accuracy of L_v, L_s, and L_f is given in Table III.

Saturation Vapor Pressures

In meteorological parlance, saturation vapor pressure refers to the partial pressure of water vapor for saturated conditions over a plane surface of either liquid or solid water. The saturation vapor pressure, expressed in millibars (conversion to other pressure units is provided in Table IV), is a function of temperature only.

The saturation vapor pressure associated with a plane liquid water surface, e_{s_w}, is approximated by

$$e_{s_w} = 10^{(a+b+c+d+e)} \quad (5)$$

where a = 23.83224
   b = $-5.02808 \log_3 T$
   c = $8.1328 \times 10^{-3} \times 10^{(3.4914 - 1302.8844/T)}$
   d = $-1.3816 \times 10^{-7} \times 10^{(11.344 - 0.0303998\,T)}$
   e = $-2949.076/T$

and the saturation vapor pressure associated with a plane solid water surface, e_{s_i}, is approximated by

---

[3] Equations 5 and 6 are restatements of those given by List [5, p. 350].

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TABLE III[4]

PERCENTAGE ERRORS IN THE NUMERICAL APPROXIMATIONS FOR CALCULATION OF LATENT HEATS

Temperature (C)	Percentage Errors in Latent Heats		
	Vaporization	Sublimation	Fusion
60	0.009		
55	0.004		
50	0.000		
45	−0.004		
40	0.009		
35	0.004		
30	0.017		
25	0.030		
20	0.043		
15	0.048		
10	0.051		
5	0.06		
0	0.074	0.000	0.063
−10	0.083	0.003	0.108
−20	0.057	−0.005	−0.080
−30	0.000	0.005	−0.246
−40	−0.153	0.005	−0.462
−50	−0.445	−0.005	0.350
−60		0.003	
−70		0.000	
−80		0.001	
−90		0.006	
−100		0.000	

[4]The comparative base for construction of this Table was that provided by List [5, p. 343].

TABLE IV[5]

PRESSURE CONVERSIONS

$$1.0 \text{ millibars (mb)} = 10^3 \text{ g cm}^{-1} \text{ sec}^{-2}$$

$$1.4504 \times 10^{-2} \text{ lb in}^{-2}$$

$$2.08854 \text{ lb ft}^{-2}$$

TABLE V[6]

PERCENTAGE ERRORS IN THE NUMERICAL APPROXIMATIONS FOR CALCULATION OF SATURATION VAPOR PRESSURE AT SELECTED TEMPERATURES

Temperature (C)	Percentage Errors	
	e_{s_w}	e_{s_i}
-100		0.003
-80		-0.015
-60		0.031
-40	0.017	0.008
-20	-0.003	-0.036
0	-0.004	-0.008
20	-0.004	
40	-0.003	
60	-0.004	
80	-0.005	
100	-0.004	

[5] The conversions given here are based on the values provided by List [5, p. 13].

[6] The comparative base for the construction of this table was that provided by List [5, pp. 351-353 and 360-361].

$$e_{s_i} = 10^{(a+b+c+d)} \qquad\qquad (6)$$

where a = 2.0702
        b = -2484.99/T
        c = 3.56654 log T
and   d = -0.0032098 T

The percentage accuracies of the functions of e_{s_w} and e_{s_i} are given in Table V[7].

Dew Point Temperature

The dew point temperature, T_d, is that which unsaturated air, cooled at constant pressure with no change in the water vapor mixing ratio, would have at saturation. The process for approximating this temperature is an iterative one, with the basis of closure being the difference between the actual vapor pressure determined from the dry bulb temperature and relative humidity and the calculated vapor pressure of the dew point temperature. Assuming that the dry bulb temperature and the relative humidity are known, the calculations are accomplished as follows:

1. Select the accuracy desired in the vapor pressure differences. The resulting number of iterations required for various accuracies are provided in Table VI.

2. Calculate the saturation vapor pressure of the dry bulb temperature, e_s, using Eq. 5.

3. Calculate the desired vapor pressure at the dew point temperature, e_a, from the relationship

$$e_a = \frac{e_s \, rh}{100} \qquad\qquad (7)$$

4. Make an initial estimate of the dew point temperature. The initial estimate in this report is found from a restatement of an approximation given by Tewson and Longley [6, p. 226]:

[7] Applying the function statements stated here to all the values provided by List [5, pp. 351-353; 360-361] the maximum percentage error found was 0.04 percent.

TABLE VI[8]

PERCENTAGE ERROR OF THE DEW POINT AND WET BULB TEMPERATURE ITERATION TECHNIQUE[9]

DEW POINT TEMPERATURE				Preset Allowable Error (vapor pressure)	WET BULB TEMPERATURE				Pressure (mb)
Average Computational Error	RMS	Number of Iterations Average	RMS		Average Error	Computational RMS	Number of Iterations Average	RMS	
0.15	0.59	3	1	1.0	-0.04	0.53	6	3	1000
-0.0025	0.053	8	3	0.1	-0.002	0.052	11	4	
-0.00033	0.0052	13	3	0.01	-0.00037	0.0053	16	4	
0.00003	0.00053	18	3	0.001	0.00001	0.00058	21	5	
-0.00000	0.00005	23	3	0.0001	-0.00000	0.00005	26	5	
				1.0	-0.03	0.54	6	3	600
				0.1	-0.0011	0.053	10	4	
				0.01	-0.0002	0.0052	16	4	
				0.001	-0.00001	0.00099	20	4	
				0.0001	-0.00000	0.00006	25	4	

[8] This table was constructed on the basis of 1150 values for each preset allowable percentage error in the final vapor pressure. Temperatures used ranged from -10C to +100C at steps of 5C combined with relative humidities ranging from 1 percent to 99 percent at steps of 2 percent.

[9] Accuracy is expressed in terms of vapor pressure percentage difference between that resulting from the iterative process and that from the relative humidity (see Eqs. (10) and (15)).

$$T_d = \frac{2340}{8.573 - \log(0.16367e_a)} \qquad (8)$$

5. Establish an initial increment for temperature iteration. The initial increment of temperature, ΔT, used in this report is determined from

$$\Delta T = 7.7 - 0.026T_d \qquad (9)$$

with the added condition that $|\Delta T| > 0.1$.

6. Calculate the saturation vapor pressure corresponding to the estimated T_d, $e_s(T_d)$, using Eq. 5 of Table V.

7. Find the error in this vapor pressure from

$$error = \frac{100 \left[e_a - e_s(T_d) \right]}{e_a} \qquad (10)$$

If this error is smaller than the value specified in Step 1, STOP: the T_d currently being investigated is acceptable as an estimate of the dew point temperature.

8. If the sign of the error has changed from the previous one and the error is larger than the value specified in Step 1, change Δt to $\frac{1}{2}\Delta T$.

9. Adjust the estimated value, T_d, according to

$$T_d = T_d + \frac{e_a - e_s(T_d)}{|e_a - e_s(T_d)|} \Delta T \qquad (11)$$

and then RETURN TO STEP 6.

The accuracy of the dew point temperature is dependent on the accuracy of Eq. 5 and the temperature of the dew point. With a closure accuracy requirement of 0.001 percent, the maximum error to be expected would range from 0.005 C at -50 C to 0.002 C at +100 C.

The percentage accuracies, exclusive of consideration of the vapor pressure function contributions, are provided in Table VI.

Wet Bulb Temperature

The wet bulb temperature, T_w, is that which unsaturated air, cooled by the adiabatic evaporation of water at constant pressure with no external source of heat, would have at saturation. Like the dew point temperature of the preceding section, the process for approximating this temperature is an iterative one, with the basis of closure being the difference in vapor pressures. Assuming that the dry bulb temperature and relative humidity are known, the calculations are accomplished as follows:

1. Select the accuracy desired in the vapor pressure differences. The resulting number of iterations required for various accuracies are provided in Table VI.

2. Calculate the saturation vapor pressure of the dry bulb temperature, e_s, using Eq. 5.

3. Calculate the vapor pressure at the dew point temperature, e_a, from the relationship stated in Eq. 7.

4. Make an initial estimate of the wet bulb temperature. The initial estimate in this report is found from a consideration of the dew point temperature, T_d, as estimated in Eq. 8, in the form

$$T_w = \frac{e_a T_a + e_s T_d}{e_a + e_s} \tag{12}$$

5. Make an initial estimate of the saturation vapor pressure of the dew point temperature, e_w, using the expression from List [5, p. 366] in the form

$$e_w = e_a + 0.000C\acute{5}\,P(1 + 0.0011\,T_w)(T_a - T_w) \tag{13}$$

6. Establish an initial increment for temperature iteration. The initial increment of temperature, ΔT, used in this report is determined from

$$\Delta T = [e_s(T_w) - e_w](3.3 - 0.0089T_a) \tag{14}$$

where $e_s(T_w)$ is found from Eq. 5, with the added condition that $|dT| > 0.2$.

7. Calculate the saturation vapor pressure corresponding to the estimated T_w, $e_s(T_w)$, using Eq. 5.

8. Calculate the vapor pressure, e_w, using Eq. 13.

9. Find the error between the two vapor pressures (from Steps 7 and 8) from

$$\text{error} = \frac{[e_s(T_w) - e_w] \; 100}{e_w} \qquad (15)$$

   If this error is smaller than the value specified in Step 1, STOP: the T_w currently being investigated is acceptable as an estimate of the wet bulb temperature.

10. If the sign of the error has changed from the previous one and the error is larger than the value specified in Step 1, change ΔT to $\frac{1}{2}\Delta T$.

11. Adjust the estimated value, T_w, according to

$$T_w = T_w + \Delta T \qquad (16)$$

   where ΔT is positive if $e_s(T_w) < e_w$ and negative if $e_s(T_w) > e_w$. RETURN TO STEP 7.

As for the dew point temperature, the accuracy of the wet bulb temperature is mainly dependent on the accuracy of Eq. 5 and the temperature of the wet bulb.

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Specific Heat of Liquid Water

The amount of heat required to raise one gram of liquid water one degree K is the specific heat of water, c_w. The function for estimating the value of c_w results from a curve fitting of the data given by List [5, p. 343]. The function is

$$c_w = 0.9979 + \frac{0.3021}{2^{(8.5-0.1\,|T-308|)}} \qquad (17)$$

The accuracy of the application of this function with the values from List [5, p. 343] is summarized in Table VII.

METEOROLOGICAL PROCESS PARAMETERS

The meteorological parameters described in this section are associated with meteorological processes. The parameters covered are: (1) the temperature air would have after it has been lifted (dry adiabatically with no change in water vapor mixing ratio) from an initial level until saturation is reached, which corresponds to the temperature of the lifting condensation level (LCL); (2) the time rate of change of the mass of freely falling water drops; and (3) the temperature resulting from moving air from one pressure level to another in a maintained saturated state, which is the psuedo-adiabatic temperature.

Temperature of the LCL

The temperature of the LCL, T_{LCL}, is computed from the dry bulb temperature, T, and the dew point temperature, T_d, of the initial level in a restatement of the formulation provided by Inman [7], namely

$$T_{LCL} = T_d + (0.098 - 0.001571\, T_d + 0.000436\, T_a)(T_a - T_d) \qquad (18)$$

TABLE VII

PERCENTAGE ERROR IN THE NUMERICAL APPROXIMATIONS FOR THE
CALCULATION OF THE SPECIFIC HEAT OF LIQUID WATER

Temperature (C)	Percentage Error of c_w
-50	0.000
-40	0.785
-30	-0.609
-20	-0.417
-10	-0.316
0	-0.006
5	0.087
10	0.132
15	0.144
20	0.146
25	0.127
30	0.108
35	0.084
40	0.108
45	0.137
50	0.176
55	0.234
60	0.322

The accuracy of the approximation is given in Table VIII, where
the comparative base is that provided by Nordquist [8].
These values were computed using an iterative scheme, which
had a closure of 0.001 percent in determination of the LCL water
vapor mixing ratio.

Change of Mass of Freely Falling Water Drops

The construction of numerical models which contain consideration
of liquid water require that some method be established for
considering the mechanism of evaporation. The parameterization
used here is based on the method proposed by Kessler [9, pp.
29-30] using the data provided by Kinzer and Gunn [10].
The basis of the approximation is that the change in mass due to
evaporation can be expressed in the form   ·

$$\frac{dM}{dT} = A\ (e_s - e_a)\ d^B \tag{19}$$

The two approximations provided here are based on "best"
fits of the Kinzer and Gunn data to Eq. (19), one as the
equation stands and the other including a temperature
dependence. The first approximation is

$$\left.\frac{dM}{dT}\right)_1 = 0.0152\ (e_s - e_a)\ d^{1.615} \tag{20}$$

while the second is

$$\left.\frac{dM}{dT}\right)_2 = \left[1. - 0.025(T_a - 290)\right]\ \left.\frac{dM}{dT}\right)_1 \tag{21}$$

The accuracy of these approximations for selected conditions is
given in Table IX, with the Kinzer and Gunn data as the
comparative base.

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TABLE VIII

ERROR (C) OF THE LIFTING CONDENSATION LEVEL
TEMPERATURE FUNCTION

Initial Temperature (C)	Initial Relative Humidity (%)				
	90	70	50	30	10
-20	-0.015	-0.015	-0.013	0.008	0.045
0	0.007	0.007	0.005	-0.002	0.009
+20	0.013	0.014	0.011	-0.004	-0.038
+40	0.021	0.029	0.030	0.004	-0.072

TABLE IX[10]

PERCENTAGE ERROR OF THE dM/dt APPROXIMATIONS FOR FREELY FALLING WATER DROPS FOR SELECTED CONDITIONS

Drop Diameter (cm)	Temperature				Relative Humidity (%)
	0 C		40 C		
	$(dM/dt)_1$	$(dM/dt)_2$	$(dM/dt)_1$	$(dM/dt)_2$	
0.02	50	29	−43	40	10
	45	29	−84	38	50
	44	28	−90	36	90
0.08	33	4	−96	17	10
	33	5	−102	15	50
	32	3	−109	12	90
0.20	32	3	−106	13	10
	32	4	−112	11	50
	31	2	−119	8	90
0.30	43	18	−84	22	10
	43	19	−89	20	50
	42	17	−96	17	90
0.36	50	29	−64	31	10
	50	29	−63	29	50
	49	28	−74	27	90

[10] While these percentage errors are quite large, they relate to rather small numbers, and are adequate for those problems where the cloud physics are treated in a gross sense.

Saturation-Adiabatic Temperatures

Air moved adiabatically from one pressure level to another in a
saturated state can take on one of two different values,
depending on the disposition of the water content of the air.
If the total water content remains constant, the process is
reversible and the resulting temperature is the saturation-adiabatic
temperature, T_s. If the total water content decreases by the amount
of liquid water present s· that the process is irreversible,
the resulting temperature is the psuedo-adiabatic temperature,
T_m.

The technique for determining these temperatures requires use
of the statement of the First Law of Thermodynamics, based on
the definitions provided by Beers [11, p. 359], in the form

$$c_p dT - \frac{RT}{(P_t - e_s)} \quad d(P_t - e_s) + T d(\frac{L_v X_s}{T}) + c_w (X_s + X_w) dT = 0 \quad (22)$$

where

$$X_s = \frac{\xi e_s}{(P_t - e_s)} \quad (23)$$

and the Clausius-Clapeyron Equation is

$$de_s = \frac{\xi L_v e_s}{RT^2} dT \quad (24)$$

Differentiation of Equations (2) and (23), and substitution
along with Equation (24) into Equation (22), yields after
rearrangement

$$\frac{dT}{dP} = \frac{RT + L_v X_s}{(P_t - e_s)\left(c_p + c_w(X_s + X_w) - 0.575 X_s + \dfrac{X_s^2 L_v^2 P_t}{RT^2 e_s}\right)} \tag{25}$$

To establish a value for the saturation-adiabatic temperature, it is assumed that no hydrometeors are within the air at the start of the process, so that $(X_s + X_w) = X_s(T_o, P_o) = X_z$. Thus

$$\frac{dT_s}{dP_t} = \frac{RT_s + L_v X_s}{(P_t - e_s)\left(c_p + c_w X_z - 0.575 X_s + \dfrac{X_s^2 L_v^2 P_t}{RT^2 e_s}\right)} \tag{26}$$

For the psuedo-adiabatic temperature, it is assumed that all the liquid water is removed from the air, so that $X_w = 0$. Thus

$$\frac{dT_m}{dP_t} = \frac{RT_m + L_v X_s}{(P_t - e_s)\left(c_p + c_w X_s - 0.575 X_s + \dfrac{X_s^2 L_v^2 P_t}{RT^2 e_s}\right)} \tag{27}$$

For many meteorological problems it is sufficient to assume that the partial pressure exerted by the air is much larger than that exerted by the water vapor included in the air, that the relative mass of the water vapor is small compared to the mass of the air, and that the latent heat of vaporization is constant. With these assumptions, Eq. (22) can be expressed as

$$c_p dT - \frac{RT}{P_t} dP_t + L_v dX_s = 0 \tag{28}$$

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and Eq. (23) can be expressed as

$$X_s = \frac{\xi e_s}{P_t} \tag{29}$$

Here T_x is used to designate this meteorological approximation to the psuedo-adiabatic temperature

$$\frac{dT_x}{dP_t} \approx \frac{RT_x + L_e x_s}{P_t \left(c_p + \frac{x_s^2 L_v^2 P_t}{RT^2 e_s} \right)} \tag{30}$$

where for each Equation (26), (27), and (30), e_s and L_y are assumed to be functions of T_s, T_m, or T_x, as appropriate.

The solution of these equations is sought by using a second-order predictor-corrector method [12, pp. 385-386][11], where the initial step is accomplished using

$$T_1 = T_o + \left.\frac{dT}{dP}\right)_o \Delta P \tag{31}$$

Thereafter, a first approximation "predictor" is made using

$$T_{i+1} = T_{i-1} + 2 \left.\frac{dT_i}{dP}\right)_i \Delta P \tag{32}$$

and the "corrector" is

[11] A systems sub-program for the Univac 1108 computer is available for accomplishing this integration in a more general manner [18, sec. 11, p.1].

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$$T_{i+1}^{n} = T_{i} + \frac{1}{2}\left[\frac{dT}{dP}\bigg|_{i} + \frac{dT}{dP}\bigg|_{i+1}\right]\Delta P \qquad (33)$$

The "corrector" is repeated until

$$\frac{(T_{i+1}^{n} - T_{i+1}^{n-1})}{T_{i+1}^{n}} \leq \text{specified closure} \qquad (34)$$

To provide some indication of the validity of this integration technique, the expression

$$\frac{dx}{dy} = 0.5\, y^{-0.5} + 1 \qquad (35)$$

was integrated from y=1 to y=30, with a Δy of 0.01 and a closure requirement of 10^{-3}. The results are given in Table X. While an accuracy analysis of the saturation- and psuedo-adiabatic temperatures is not possible due to a lack of a suitable comparative base, it is possible to compare the results with those obtained by another approximation method [5, p. 318]. The comparisons are given in Table XI and include the values provided by List [5, pp. 320-321] for psuedo-adiabatic temperatures with initial conditions of 1096.7 mb and 14C, program requirements of $\Delta p = 2$ mb, and a closure requirement of 10^{-3}.

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TABLE X

COMPARISON OF THE RESULTS OF THE NUMERICAL METHOD FOR SOLVING A
DIFFERENTIAL EQUATION APPLIED TO $dx/dy = \frac{1}{2} y^{-\frac{1}{2}} + 1$

Value of y	Initial Value of y	Value of x		Difference of Values of X
		Integration	$x = y^{\frac{1}{2}} + y$	Percentage
2	1	3.41421	3.41421	−0.00004
4	1	6.00000	6.00000	−0.00006
6	1	8.44949	8.44949	−0.00006
8	1	10.82843	10.82843	−0.00006
16	1	20.00000	20.00001	−0.00005
25	1	30.00000	30.00001	−0.00004
30	1	35.47723	35.47723	−0.00002

TABLE XI

COMPARISONS OF SATURATION-ADIABATIC TEMPERATURES (C)

PRESSURE	PSUEDO-ADIABATIC		SATURATED-ADIABATIC	
	LIST	CALCULATED	CALCULATED	MET APPROX
1096.7	14.0	14.0	14.0	14.0
1046.7	12.0	12.0	12.0	12.0
1000.0	10.0	10.1	10.0	10.0
957.0	8.0	8.1	8.1	8.1
915.0	6.0	6.1	6.1	6.1
876.0	4.0	4.2	4.1	4.1
840.0	2.0	2.2	2.2	2.1
805.0	.0	.2	.1	.1
773.0	-2.0	-1.7	-1.8	-1.9
744.0	-4.0	-3.6	-3.7	-3.8
715.0	-6.0	-5.6	-5.7	-5.8
688.0	-8.0	-7.5	-7.7	-7.8
663.0	-10.0	-9.4	-9.6	-9.7
638.0	-12.0	-11.4	-11.7	-11.8
616.0	-14.0	-13.3	-13.6	-13.7
595.0	-16.0	-15.2	-15.5	-15.6
573.0	-18.0	-17.2	-17.6	-17.8
554.0	-20.0	-19.1	-19.6	-19.7
536.0	-22.0	-20.9	-21.5	-21.6
518.0	-24.0	-22.9	-23.5	-23.6
502.0	-26.0	-24.7	-25.3	-25.5
485.0	-28.0	-26.7	-27.4	-27.6
470.0	-30.0	-28.5	-29.3	-29.5
454.0	-32.0	-30.6	-31.4	-31.6
440.0	-34.0	-32.4	-33.4	-33.5
426.0	-36.0	-34.4	-35.4	-35.5
413.0	-38.0	-36.2	-37.3	-37.5
400.0	-40.0	-38.1	-39.3	-39.4
387.5	-42.0	-40.0	-41.3	-41.4

TABLE XI (con)

COMPARISONS OF SATURATION-ADIABATIC TEMPERATURES (C)

PRESSURE	PSUEDO-ADIABATIC		SATURATED-ADIABATIC	
	LIST	CALCULATED	CALCULATED	MET APPROX
375.3	-44.0	-42.0	-43.3	-43.4
363.5	-46.0	-43.9	-45.3	-45.4
352.1	-48.0	-45.8	-47.2	-47.4
341.0	-50.0	-47.7	-49.2	-49.4
330.2	-52.0	-49.6	-51.2	-51.4
319.7	-54.0	-51.5	-53.2	-53.4
309.5	-56.0	-53.4	-55.2	-55.4
299.6	-58.0	-55.3	-57.2	-57.3
289.9	-60.0	-57.2	-59.2	-59.3
280.5	-62.0	-59.1	-61.2	-61.3
271.3	-64.0	-61.0	-63.1	-63.3
262.3	-66.0	-62.9	-65.1	-65.3
253.6	-68.0	-64.7	-67.1	-67.3
245.1	-70.0	-66.6	-69.1	-69.3
236.8	-72.0	-68.5	-71.1	-71.3
228.7	-74.0	-70.3	-73.1	-73.2
220.8	-76.0	-72.2	-75.1	-75.2
213.2	-78.0	-74.0	-77.1	-77.2
205.7	-80.0	-75.8	-79.1	-79.2
198.4	-82.0	-77.7	-81.1	-81.2
191.3	-84.0	-79.5	-83.0	-83.2
184.3	-86.0	-81.3	-85.0	-85.2
177.6	-88.0	-83.0	-87.0	-87.2
171.0	-90.0	-84.8	-89.0	-89.2
164.6	-92.0	-86.5	-91.0	-91.2
158.4	-94.0	-88.3	-93.0	-93.2
152.4	-96.0	-89.9	-95.0	-95.1

CONCLUDING REMARKS

This report has presented numerical techniques for approximating the values of several meteorological parameters along with the accuracies of the results of the approximations. This has been done so that (1) the methods might be documented for use by others, (2) the representativeness of the results of applying the techniques might be made available for analysis for other purposes, and (3) the comparison of these techniques with others can be readily accomplished.

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APPENDIX

COMPUTER LANGUAGE LISTINGS OF FUNCTIONS AND SUBROUTINES

NUMERICAL APPROXIMATIONS

+++ FUNCTION STATEMENTS +++

```
TX = DRY BULB TEMPERATURE (K)
TZ = DEW POINT TEMPERATURE(K)
ES    SATURATION VAPOR PRESSURE  (MB)
EA    ACTUAL VAPOR PRESSURE      (MB)
DIA   WATER DROP DIAMETER         (M)
```

.....LATENT HEAT OF VAPORIZATION.....

HEATV(TX)= 754.817 - 0.575*TX   1

.....LATENT HEAT OF SUBLIMATION.....

HEATS(TX)= 98.777 +SQRT(335566.953 - ABS(TX - 238.)**2.)   2

.....LATENT HEAT OF FUSION.....

HEATF(TX)=TX*(1.7757-0.0023245*TW)-0.012*ABS(TX-243.)-231.494   3

.....SATURATION VAPOR PRESSURE OVER WATER.....

SATVP(TX)=10.**(23.83224-2949.076/TX -5.02808*ALOG10(TX)   4
1   -1.3816E-7*10.**(11.3440 - 0.0303998*TX)   5
2   +8.1328E-3*10.**(3.49149 - 1302.8844/TX))   6

.....SATURATION VAPOR PRESSURE OVER ICE.....

SATVI(TX)=10.**(2.0702-2484.991/TX+3.56654*ALOG10(TX)-.0032098*TX)   7
```

# NUMERICAL APPROXIMATIONS

.....TEMPERATURE OF THE LIFTING CONDENSATION LEVEL...... 8

TLCL(TX,TZ)=TZ+(0.098-0.001571*TZ+0.000436*TX)*(TX-TZ)

.....SPECIFIC HEAT OF LIQUID WATER...... 9

SPH2O(TX)=0.9979+0.3021/(2.**(8.5-0.1*ABS(TX-308.16)))

.....DM/DT FOR FREELY FALLING WATER DROPS...... 

1.  TEMPERATURE INDEPENDENT   10

DMDT(ES,EA,DIA)=0.0152*(ES-EA)*DIA**1.615

2.  TEMPERATURE DEPENDENT   11

DMDTT(ES,EA,DIA,TX)=DMDT(ES,EA,DIA)*(1.-0.025*(TX-290.))

NUMERICAL APPROXIMATIONS

SUBROUTINE DEWPT(T,RH,ET,TD)

```
      ESTIMATING DEW POINT TEMPERATURES
      E     ACTUAL VAPOR PRESSURE -ESTIMATE    MB
      EA    ACTUAL VAPOR PRESSURE              MB
      ES    SATURATION VAPOR PRESSURE          MB
      ET    ALLOWABLE PERCENTAGE ERROR         PERCENT
      DEL   TEMPERATURE INCREMENT
      RH    RELATIVE HUMIDITY                  PERCENT
      T     TEMPERATURE - DRY BULB             K
      TD    TEMPERATURE - DEW POINT            K

      SATVP(TX)=10.**(23.83224 -2949.076/TX
     1   -5.02808*ALOGIO(TX)
     2   -1.3816E-7*10.**(11.344-.0303998*TX)
     3   +8.1328E-3*10.**(3.49149-1302.8844/TX))

      ES=SATVP(T)
      EA=RH*ES/100.
      C =0
      TD=2340./(8.573-ALOGIO(0.16367*EA))
      IF (RH.GE.100.) TD=T
      DEL=7.7-.026*TD
      IF(ABS(DEL).LT.0.I) DEL=0.I
    1 E=SATVP(TD)
      D=(E-EA)*100./EA
      IF(ABS(D).LT.ET)  RETURN
      G=C*D
      IF(G.LT.0.) DEL=DEL*0.5
      R=100.*E/ES
      TD=TD+(RH-R)*ABS(DEL/(RH-R))
      C=D
      GO TO I
      END
```

```
      SUBROUTINE WETBLB(T,P,RH,ET,TW)                              34

            ESTIMATING WET BULB TEMPERATURE

      DEL        TEMPERATURE INCREMENT                 K
      E          ACTUAL VAPOR PRESSURE -ESTIMATE       MB
      EA         ACTUAL VAPOR PRESSURE -WET BULB       MB
      EB         ACTUAL VAPOR PRESSURE -DEW POINT      MB
      ES         SATURATION VAPOR PRESSURE             MB
      ET         ALLOWABLE PERCENTAGE ERROR            PERCENT
      P          PRESSURE                              MB
      RH         RELATIVE HUMIDITY                     PERCENT
      T          TEMPERATURE - DRY BULB                K
      TW         TEMPERATURE - WET BULB                K

      SATVP(TX)=10.**(23.83224 -2949.076/TX                        35
     1           -5.02808*ALOG10(TX)                               36
     2           -1.3816E-7*10.**(11.344-.0303998*TX)              37
     3           +8.1328E-3*10.**(3.49149-1302.8844/TX))           38
      ALIST(PX,DX,TX)=0.00066*(1.+.00115*TX)*PX*DX                 39

      ES=SATVP(T)                                                  40
      EA=RH*EX/100.                                                41
      EB=EA                                                        42
      TW=2340./(8.573-ALOG10(0.16367*EA))                          43
      TW=(TW*ES+T*EA)/(EA+ES)                                      44
      IF(RH.GE.100) TW=T                                           45
      DE=T-TW                                                      46
      EK=EA+ALIST(P,DE,TW)                                         47
      DEL=(SATVP(TW)-EK)*(3.3-.009*T)                              48
      IF(ABS(DEL).LT.0.2) DEL=0.2                                  49
    1 E=SATVP(TW)                                                  50
      DE=T-TW                                                      51
      EA=EB+ALIST(P,DE,TW)                                         52
      D=(E-EA)*100./EA                                             53
```

NUMERICAL APPROXIMATIONS

```
IF(ABS(D).LT.ET)        RETURN          54
G=C*D                                   55
DEL=ABS(DEL)                            56
IF(G.LT.0.) DEL=DEL*.5                  57
IF(EA.LT.E) DEL=DEL                     58
TW=TW+DEL                               59
C=D                                     60
GO TO 1                                 61
END                                     62
```

NUMERICAL APPROXIMATIONS

```
      SUBROUTINE ADIAB(TI,PI,P2,L,TSAT)                                    63

C     TO CALCULATE SATURATION-ADIABATIC TEMPERATURE FROM
C     TEMPERATURE TI AT PRESSURE PI TO PRESSURE P2
C     FOR L=I   PSUEDO-ADIABATIC PROCESS        .    .    .
C           2   SATURATION ADIABATIC PROCESS    .    .
C           3   MET APPROXIMATION                    .

C     REFERENCE INTEGRATION TECHNIQUE
C               RITGER AND ROSE
C     DIFFERENTIAL EQUATIONS WITH APPLICATIONS
C               (MCGRAW-HILL,1968)
C               PP. 385-386

C     .....FUNCTION REQUIREMENTS.....
      EXTERNAL DTDP                                                        64
      SATVP(TX)=10.**(23.83224-5.02808*ALOG10(TX)-1.3816E-7*10.**(11.344   65
     1-.0303998*TX)+8.1328E-3*10.**(3.49149-1302.8844/TX)-2949.076/TX)     66
C     .....STORAGE REQUIREMENTS.....
      COMMON/AA/XAI                                                        67
      DIMENSION TX(3),PX(3),TZ(20)                                         58

C                  INITIALIZE
      ERRORT=1.E-3                                                         69
      I=I                                                                  70
      IX=I                                                                 71
      KI=I                                                                 72

C                  INITIAL CONDITIONS
      XAI=SATVP(TI)                                                        73
      XAI=.62197*XAI/(PI-XAI)                                              74
      PX(I)=PI                                                             75
      TX(I)=TI                                                             76
      DELDP=P2-PI                                                          77

C                  NEW INITIAL CONDITIONS
```

NUMERICAL APPROXIMATIONS

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```
       DP= ABS(DELDP)*1.E-6/DELDP                              78
       PX(2)=PX(1)+DP                                          79
       TX(2)=TX(1)+DP*DTDP(TX(1),PX(1),L)                      80
       PXREF=PX(2)                                             81
       IP=ABS(DELDP)*0.5                                       82
       IF(IP.LT.1) IP=1                                        83
                   SUCCEEDING CONDITIONS
   1   DO 5 K=IX,IP                                            84
       DP=IP                                                   85
       DP=(P2  -PXREF)/DP                                      86
       IF(ABS(DP).LT.1.E-12)  GO TO 7.                         87
       PX(I+2)=PX(I+1)+DP                                      88
       DF=DTDP(TX(I+1),PX(I+1),L)                              89
       TX(I+2)=TX(I)+2.*DP*DF                                  90
       TZ(1)=TX(I+2)                                           91
       LL=L                                                    92
                          CLOSURE ITERATIONS
       DO 2 M=2,20                                             93
       KI=KI+1                                                 94
       MM=M                                                    95
       DTDP2=DTDP(TZ(M-1),PX(I+2),L)                           96
       TZ(M)=TX(I+1)+0.5*DP*(DF+DTDP2)                         97
       TZR=ABS((TZ(M)-TZ(M-1))/TZ(M))                          98
       IF(TZR.LT.ERRORT)  GO TO 3                              99
   2   CONTINUE                                                100
       WRITE(6,998)  TX(I+1),TZ(M-1),TZ(M),TZR,I,K,M           101
 998   FORMAT(1H 4F10.5.316)                                   102
                       DID NOT CONVERGE HALVE DP
       IX=LL                                                   103
       IP=IP*2                                                 104
       GO TO 6                                                 105
   3   TX(I+2)=TZ(MM)                                          106
       DO 4  N=2.3                                             107
       TX(N-1)=TX(N)                                           108
   4   PX(N-1)=PX(N)                                           109
```

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```
  5   CONTINUE                                                        110
      TSAT=TX(I+2)                                                    111
      WRITE(6,999) KI                                                 112
999   FORMAT(1H+90XI9)                                               113
      RETURN                                                         114
  6   GO TO 1                                                        115
  7   WRITE(6,8) PX(I+2),TX(I+2),KI,DP,T1,P1,P2                      116

  8   FORMAT(1H /29H THIS DID NOT CONVERGE AT P =F8.1,8H AND T =F9.2/1X   117
     1 3HON I5,24H ITERATIONS OF DELTA P =1PE12.5/1X                 118
     2 13HGOING FROM T=0PF8.1, 3H P=F8.1,  6H TO P=F8.1)             119

      RETURN                                                         120
      END                                                            121
```

35

NUMERICAL APPROXIMATIONS

```
FUNCTION DTDP(T,P,IX)                                    122

FUNCTION FOR THE CALCULATION OF THE CHANGE OF SATURATED-ADIABATIC
TEMPERATURE WITH PRESSURE UNDER THREE BASIC SETS OF CONDITIONS

      .....STORAGE REQUIREMENTS......

COMMON/AA/XI                                             123

                      FUNCTION REQUIREMENTS

HEATV(TX)=754.817-.575*TX                               124
SATVP(TX)=10.**(23.83224-5.02808*ALOGIO(TX)-1.3816E-7*10.**(11.344    125
1-.0303998*TX)+8.1328E-3*10.**(3.49149-1302.8844/TX)-2949.076/TX)     126

A=.068557*T                                             127
E=SATVP(T)                                              128
H=HEATV(T)                                              129
XA=XI                                                   130
CX=-.575                                                131
TXX=ABS(T-380,16)                                       132
  CW=0.9979+0.3021/(2.**(8.5-0.1*TXX))                  133
PB=P-E                                                  134
IF(IX.EQ.3) PB=P                                        135
X=0.62197*E/PB                                          136
CP=.2399+.4409*X                                        137
IF(IX.EQ.2)  XA=X                                       138
IF(IX.EQ.3)  XA=0.                                      139
IF(IX.EQ.3)CX=0.                                        140
AI=(A+H*X)/PB                                           141
BL=X*X*H*H*P/(A*T*E)                                    142

DTDP=AI/(CP+CW*XA+CX*X+BI)                              143

RETURN                                                  144
END                                                     145
```

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